Primary Batteries for Emerging Deep Space Exploration Missions

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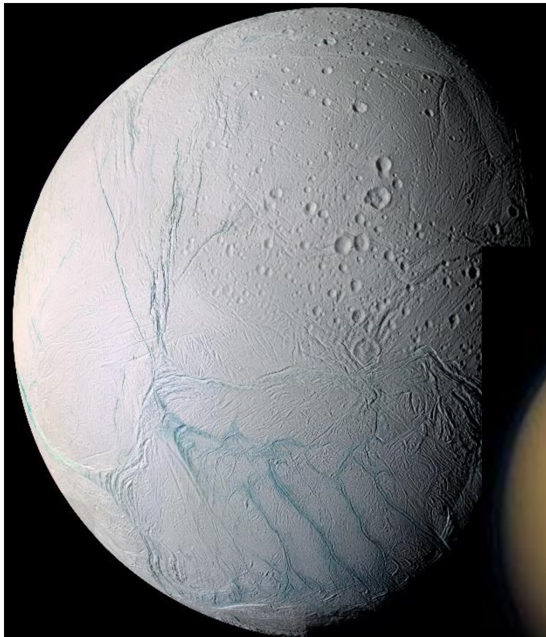
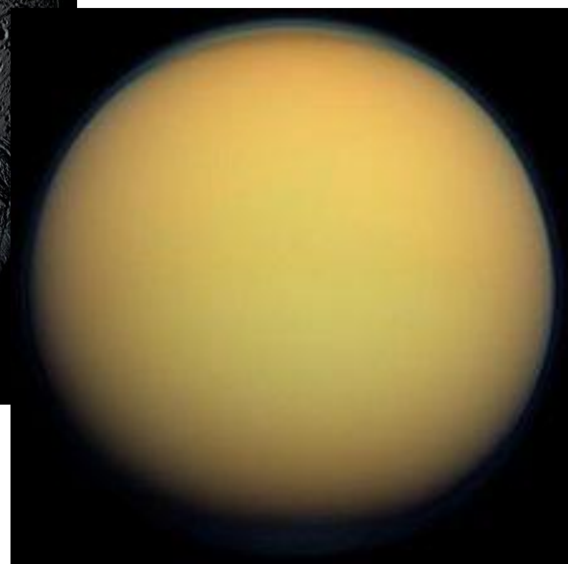
Outline

- Motivation for work
- Screening for performance vs. temperature
- Calorimetry/heat evolution during discharge
- Radiation testing

Increasing Interest in Ocean Worlds



Enceladus

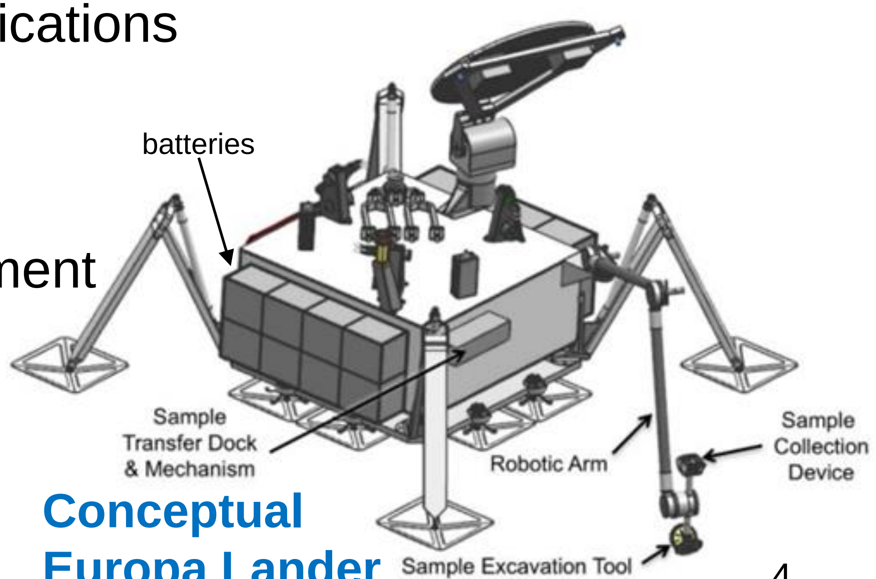


Titan

Europa

Primary Batteries for Potential Future Landers

- **High specific energy**
  - Extreme distance from Sun and lander mass considerations suggest mission concepts powered only by a primary battery
  - 10-20 day mission timeline requires high specific energy to keep battery mass low
- **Wide temperature operation**
  - Low temperature applications
  - Moderate to high temperature applications
- **Radiation tolerance**
  - Planetary protection protocol
  - High radiation operational environment



Conceptual Europa Lander

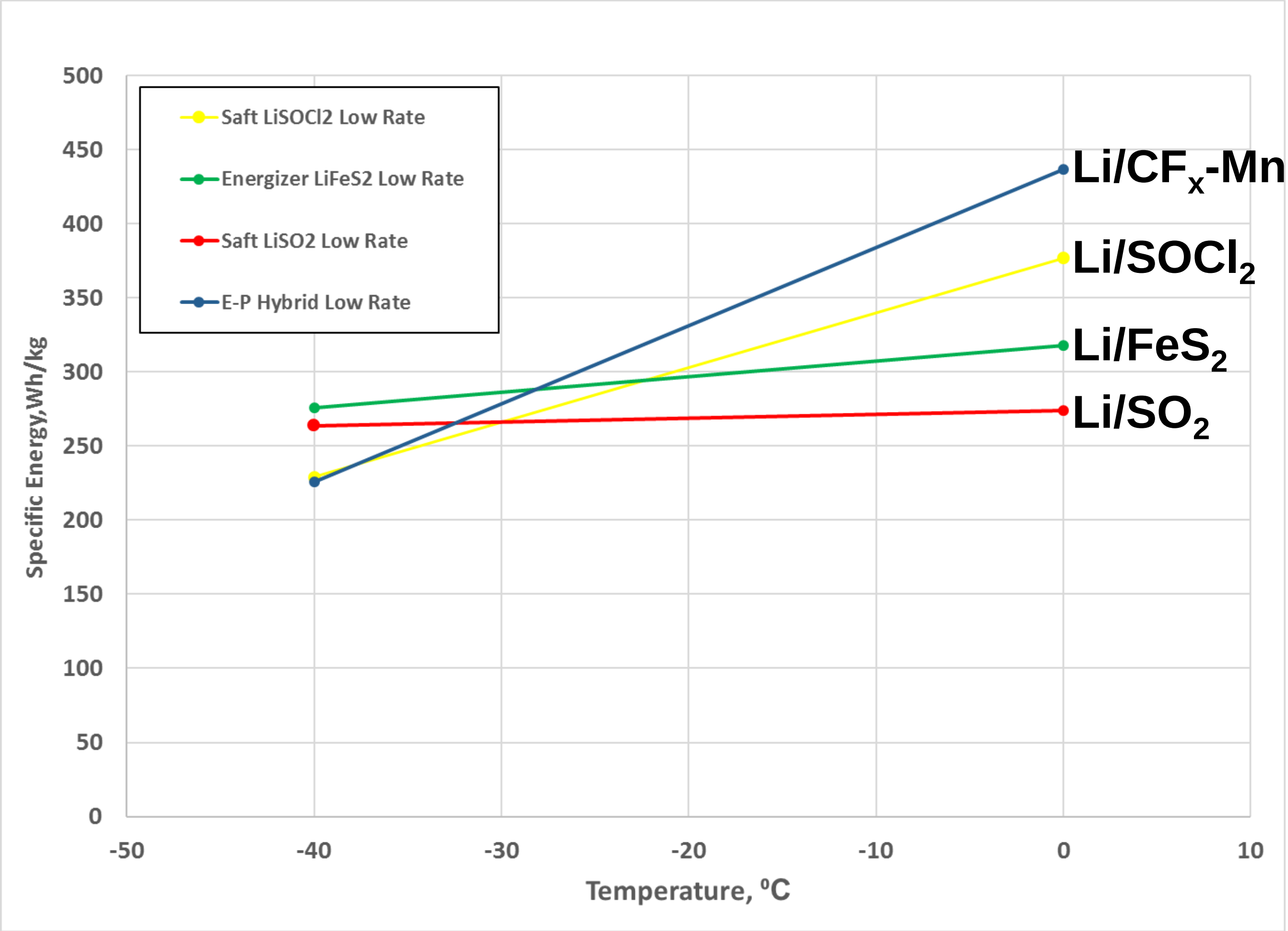
Pre-decisional information for planning and discussion only

Evaluation of Cell Options

Cell Chemistry	Vendor	Part Number	Format
Li/SO_2	Saft	LO 26 SXC	D cell
$Li/SOCl_2$	Saft	LSH 20	D cell
Li/FeS_2	Energizer	L91	AA cell
Li/MnO_2	Ultralife	CR15270	D cell
$Li/CF_x\text{-}MnO_2$	Eagle-Picher	LCF-133 (COTS and modified)	D cell
Li/CF_x	Ray-O-Vac	DP-BR-20Al	D cell

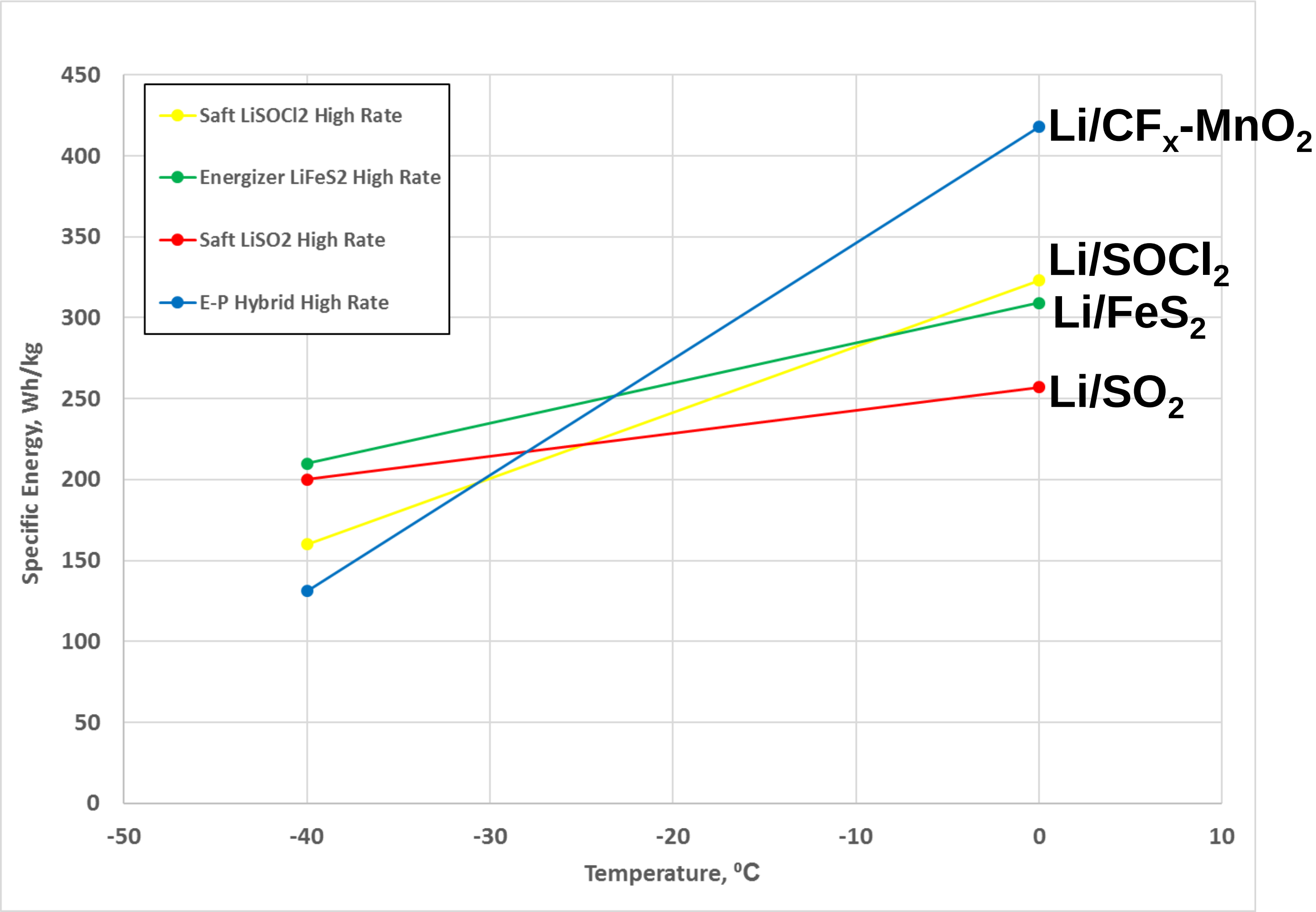
Initially targeted high specific energy at moderate rates (50-600 mA for a D cell) and temperatures of -40 to +30°C

Moderate Rate Discharge ~C/300 between -40ºC and 0ºC



- At lowest temperatures, Li/FeS_2 delivers the highest specific energy
- At ~-30ºC there is a cross-over, and Li/CF_x-MnO_2 is highest

Moderate Rate Discharge
~C/60 between -40ºC and 0ºC

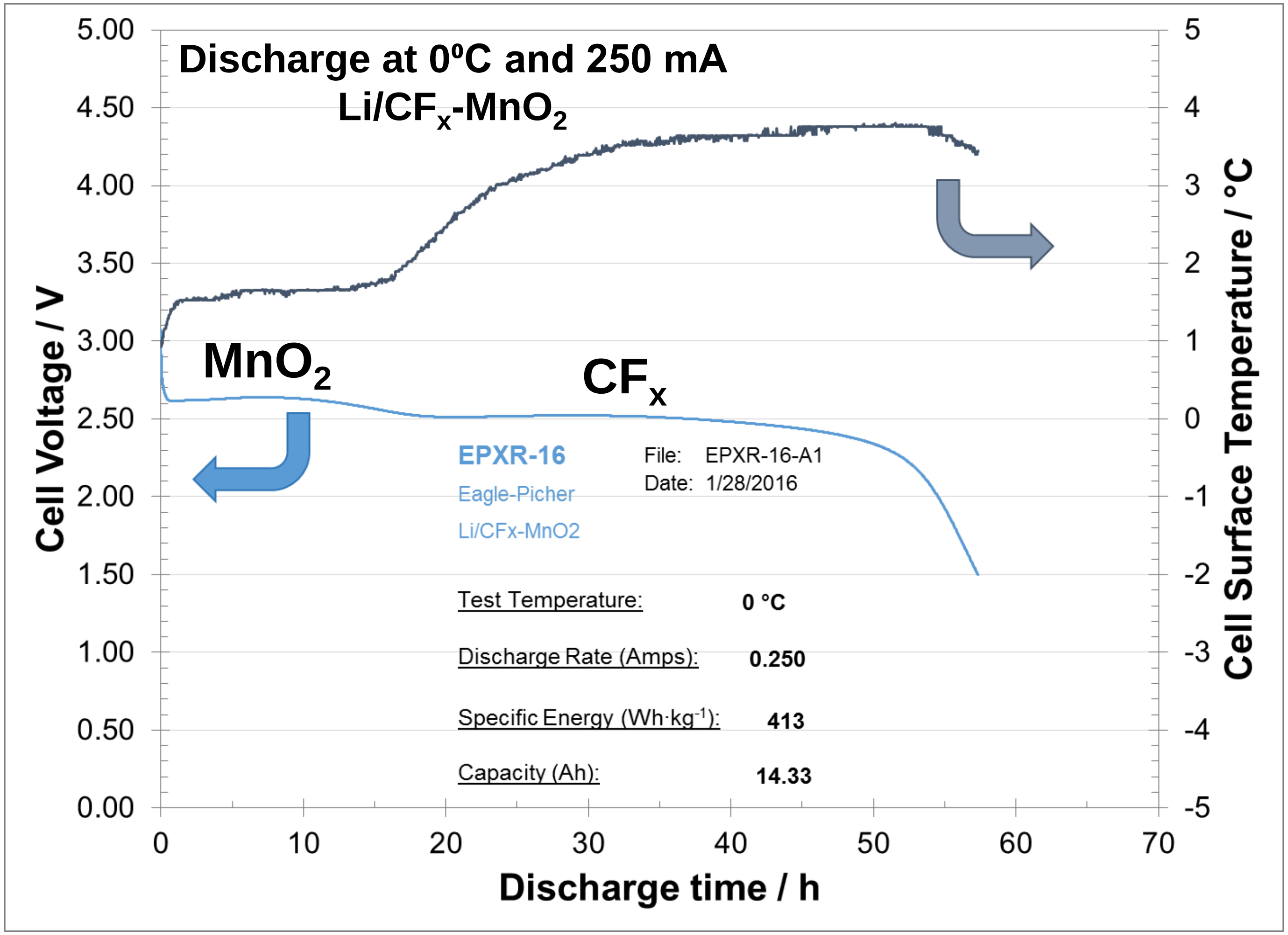


- **Similar situation at higher rates**
- **Li/CF$_x$-MnO$_2$ significantly higher performance at 0ºC**

Evolving System and Power Requirements

- As system trade studies evolved, nominal operating temperature increased, along with mission timeline (need more energy)
- Low temperature, moderate duration (original design)
  - Temperature: -40ºC, Mission timeline: 5-10 days
- Moderate temperature, long duration (updated design)
  - Temperature: >0ºC, Mission timeline: 10-20 days
- Hybrid Li/CF_x-MnO_2 was clear choice
  - Start evaluating heat output/thermal considerations

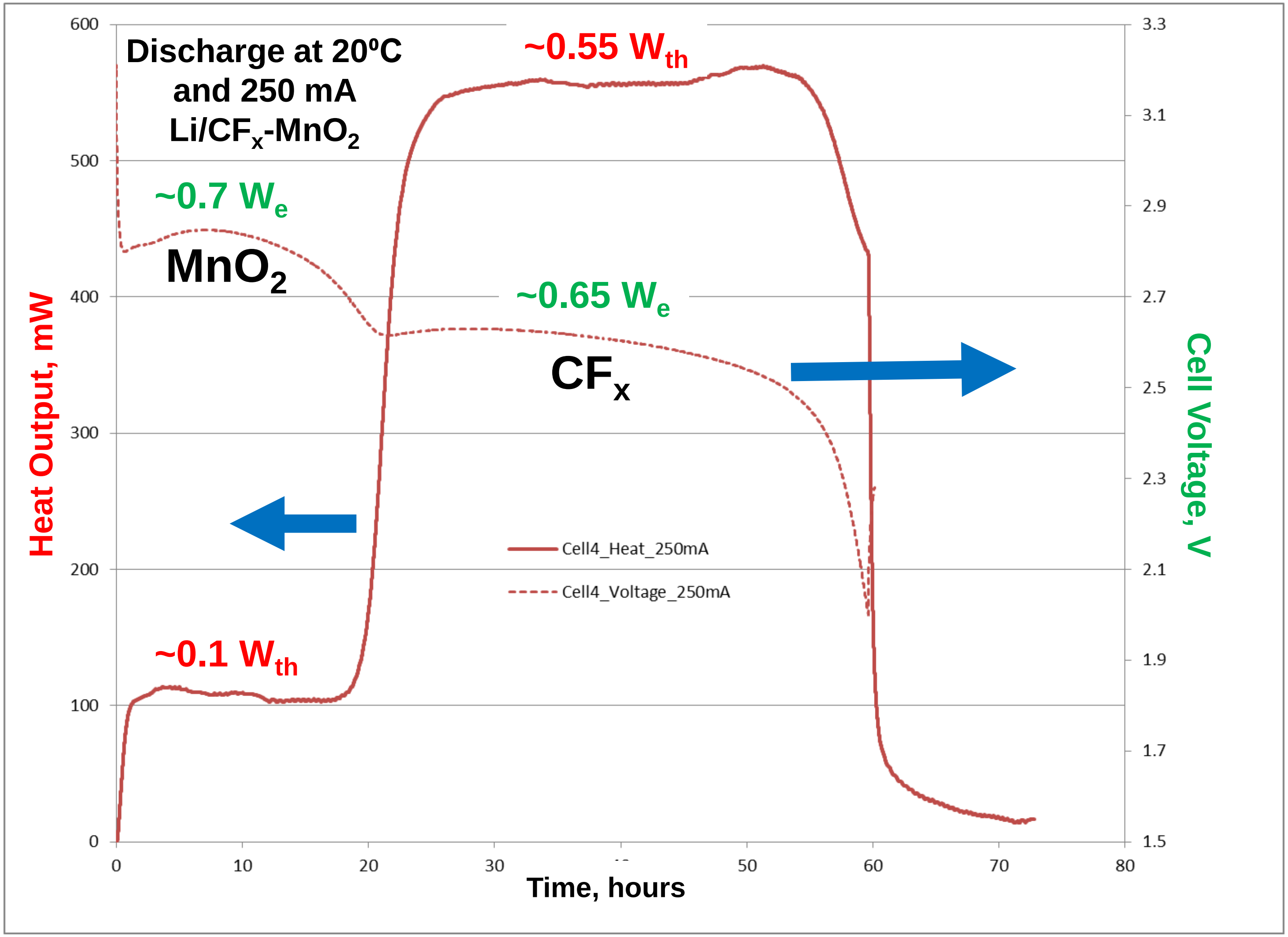
Li/CF_x-MnO_2 Discharge Testing



Environmental Chamber

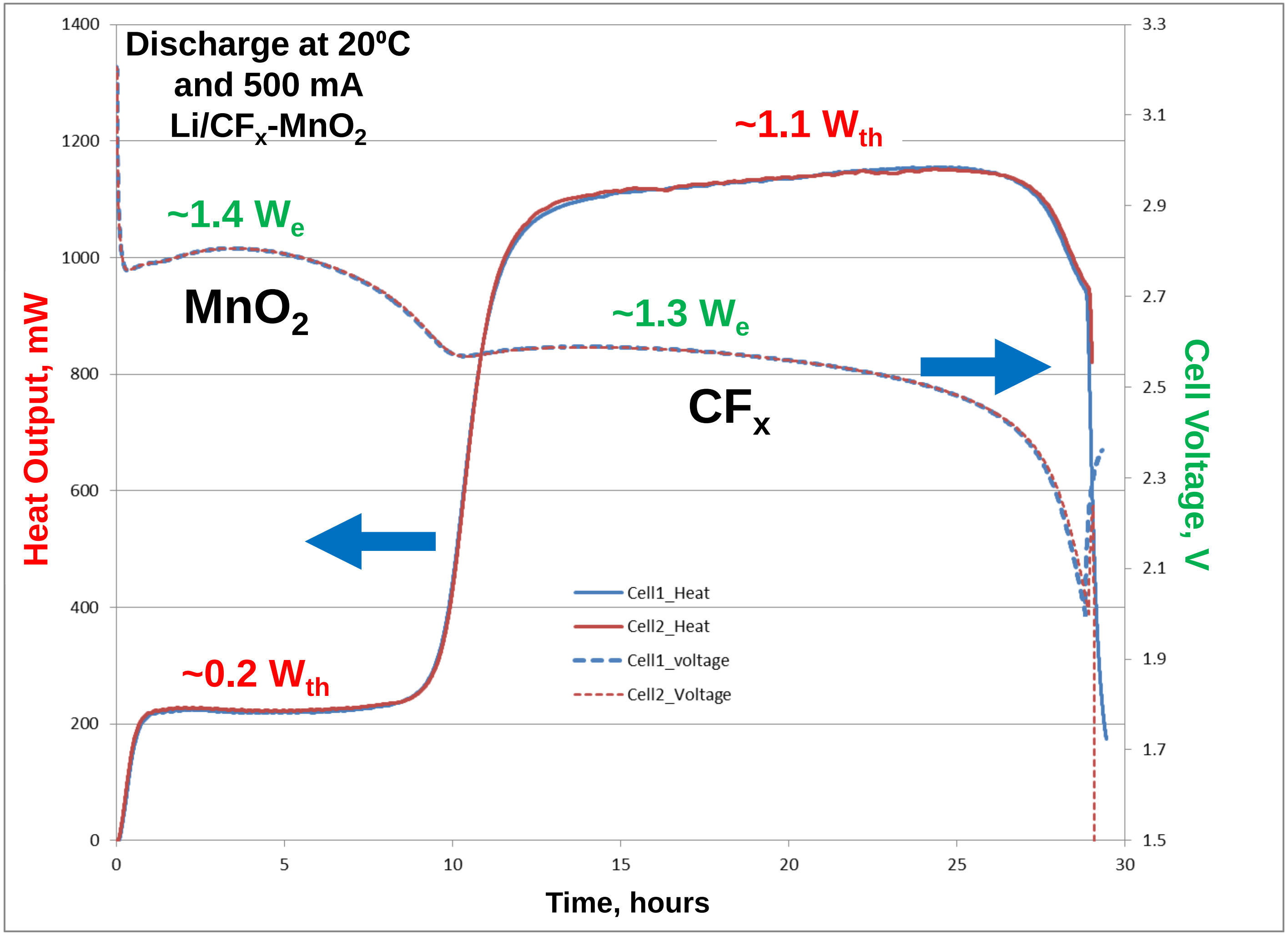
Slight temperature rise observed via attached thermocouples, during discharge in large convectively cooled chamber

Calorimetry of Li/CF_x-MnO_2



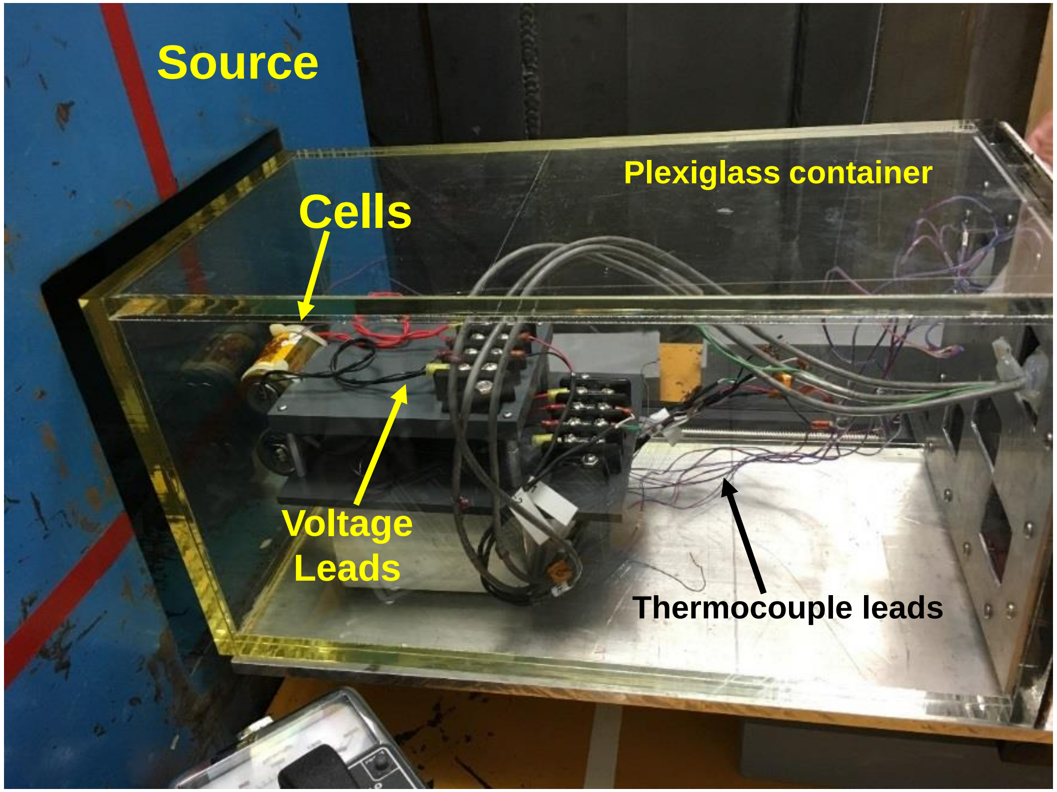
Significant heat generation observed from CF_x plateau during isothermal calorimetry

Calorimetry of Li/CF_x-MnO_2



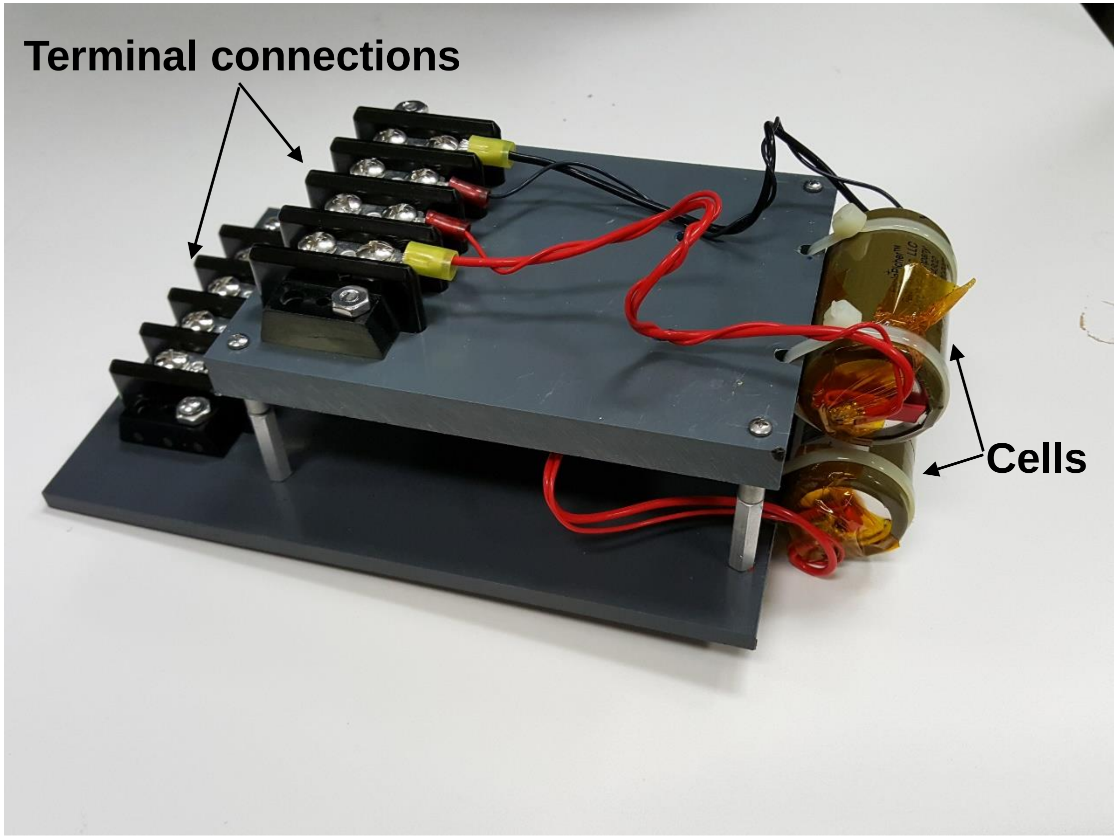
Higher heat output at higher rate discharge

Radiation Test Set-Up



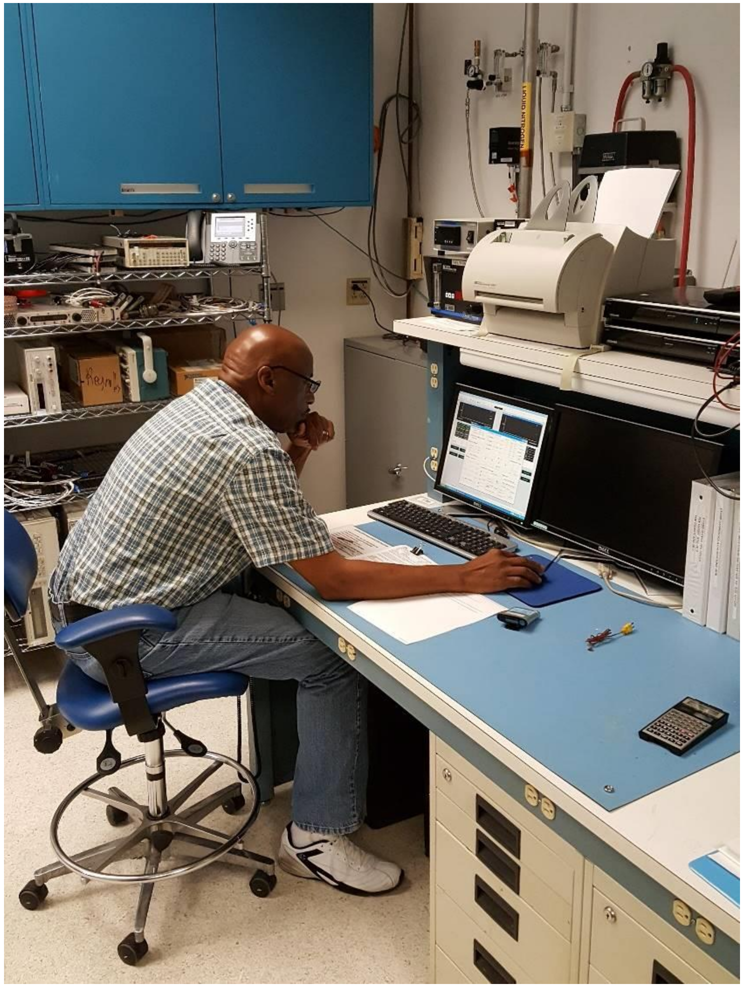
- Plexiglass container
- Continuous nitrogen purge
- Mounted on motorized track for remote removal from source

Radiation Test Fixture



Radiation test fixture for two D-cells

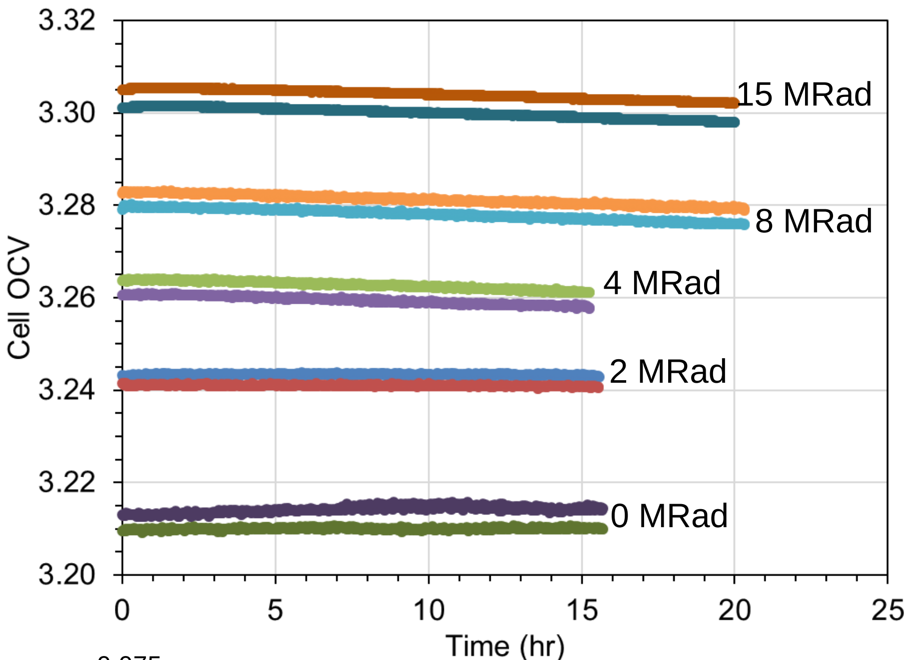
Monitoring During Radiation Dose



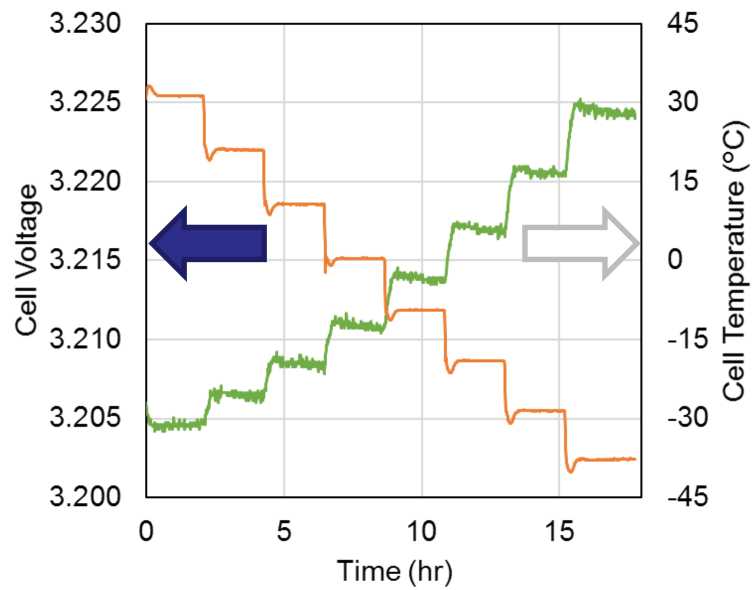
Bernie Rax (Radiation Test Engineer)

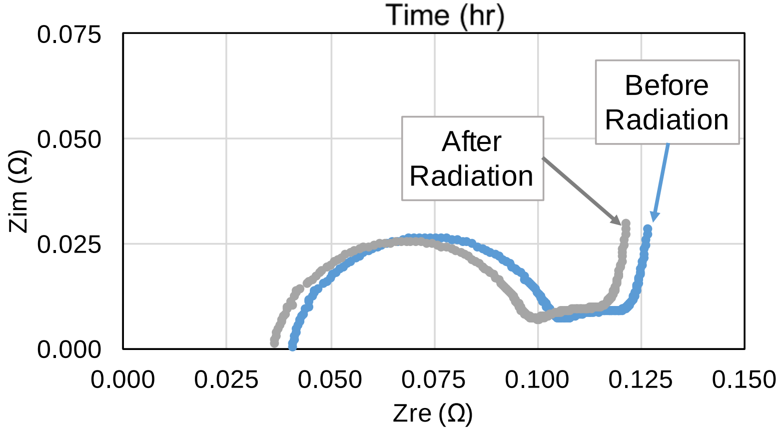
- Open circuit voltage and temperature measured during dose
- If temperature or OCV exceeds limits, cells are pulled from the source

Eagle-Picher Li/CF_x-MnO_2 cells: radiation exposure Effects of Irradiation on OCV and Impedance



- Rise in OCV proportional to irradiation
- Irradiation also causes cell heating; however, manually heating a non-irradiated cell in a stepwise fashion reveals that increased temperature causes lower OCV:

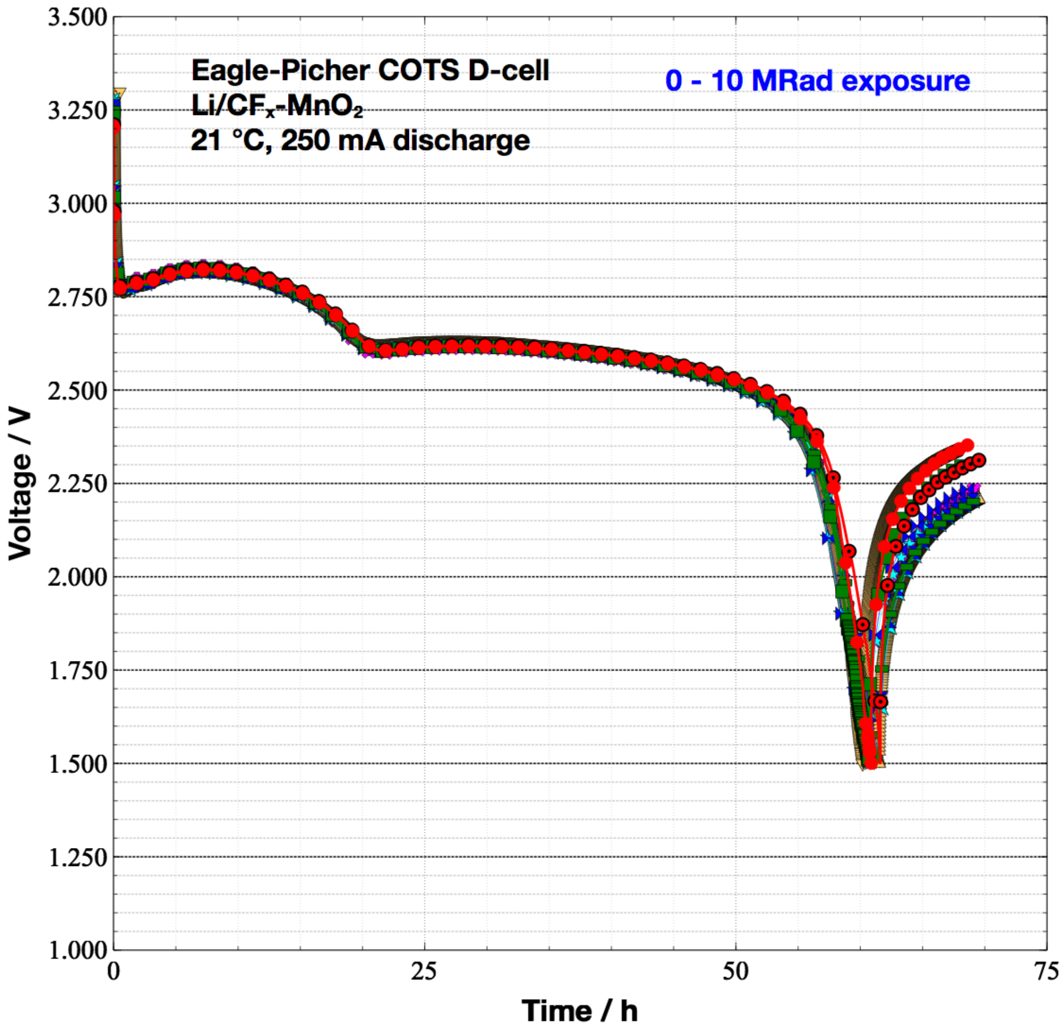




- Temperature is not the cause of OCV rise
- No change in impedance after radiation

From: F. Krause, et al. *"Evaluation of Commercial High Energy Lithium Primary Cells for Wide Temperature Range Aerospace Applications*," 231st Meeting of the Electrochemical Society, New Orleans, Louisiana, May 31, 2017

Eagle-Picher Li/CF_x-MnO_2 cells: radiation exposure No irradiation ➞ 10 Mrad exposure



- 10 cells were irradiated to either 1, 2, 4, 8, or 10 Mrad
- Discharge at 21 ºC, 250 mA, along with two non-irradiated cells
- Very similar discharge performance
- Discharge profiles show no significant changes up to 10 Mrad exposure

From: F. Krause, et al. *“Evaluation of Commercial High Energy Lithium Primary Cells for Wide Temperature Range Aerospace Applications*,” 231st Meeting of the Electrochemical Society, New Orleans, Louisiana, May 31, 2017

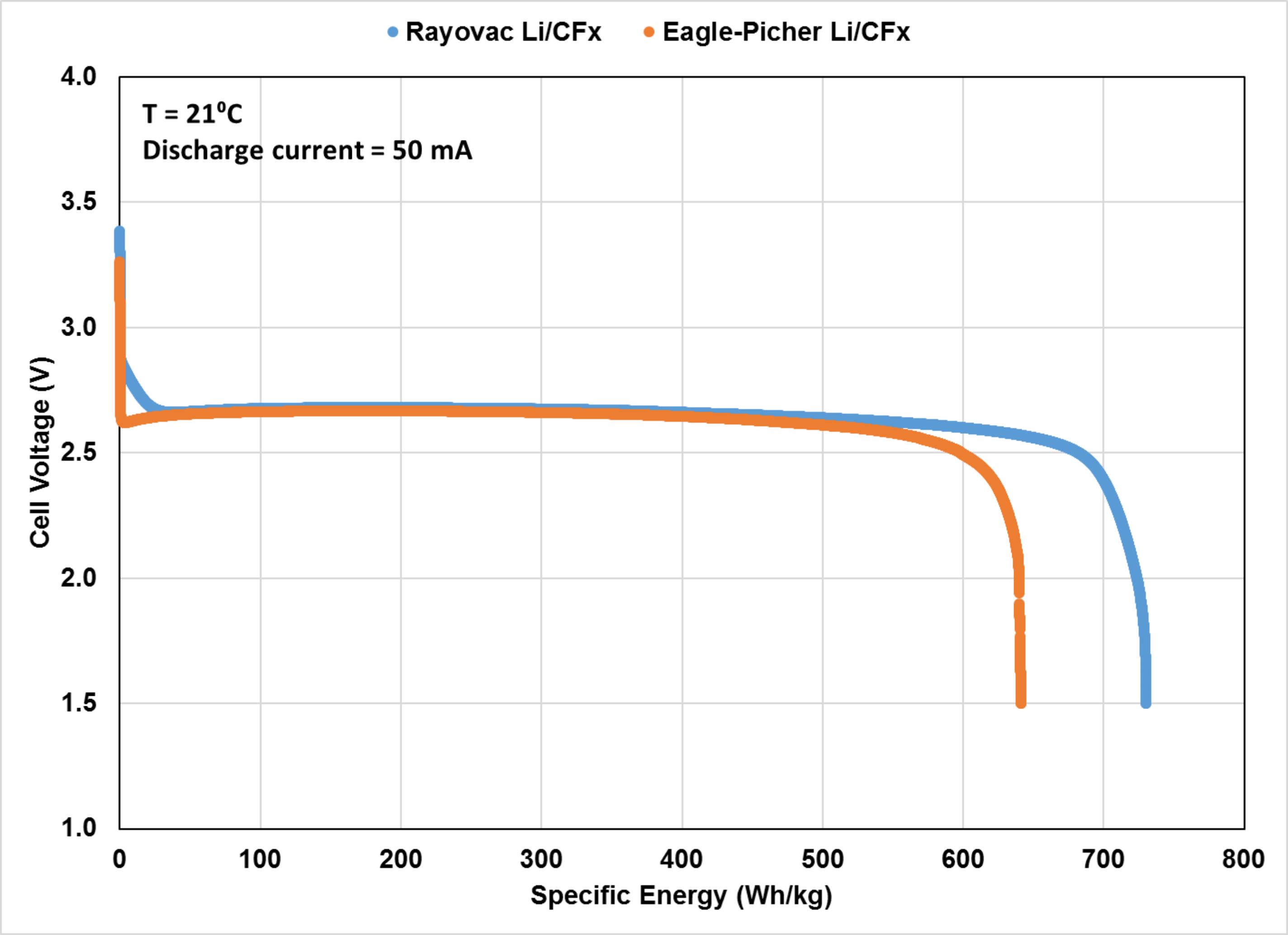
Effects of Radiation on Li/CF_x-MnO_2 Cells

- Previously reported data indicated shift in OCV with total dose (Krause, Spring ECS 2017)

- No significant impact on beginning-of-life capacity delivered

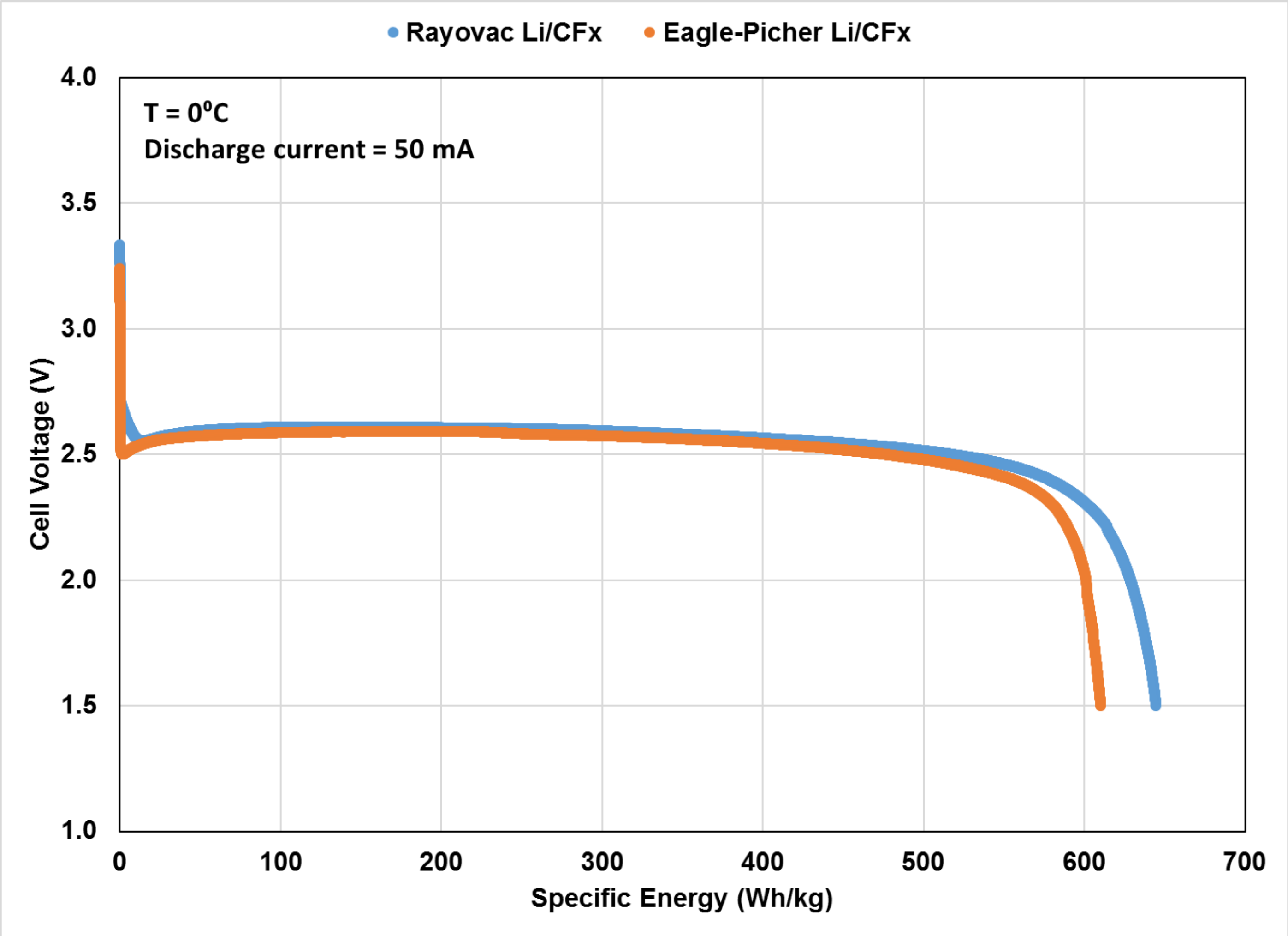
- Now looking at pure CFx

Li/CF_x discharge at +21ºC and 50 mA



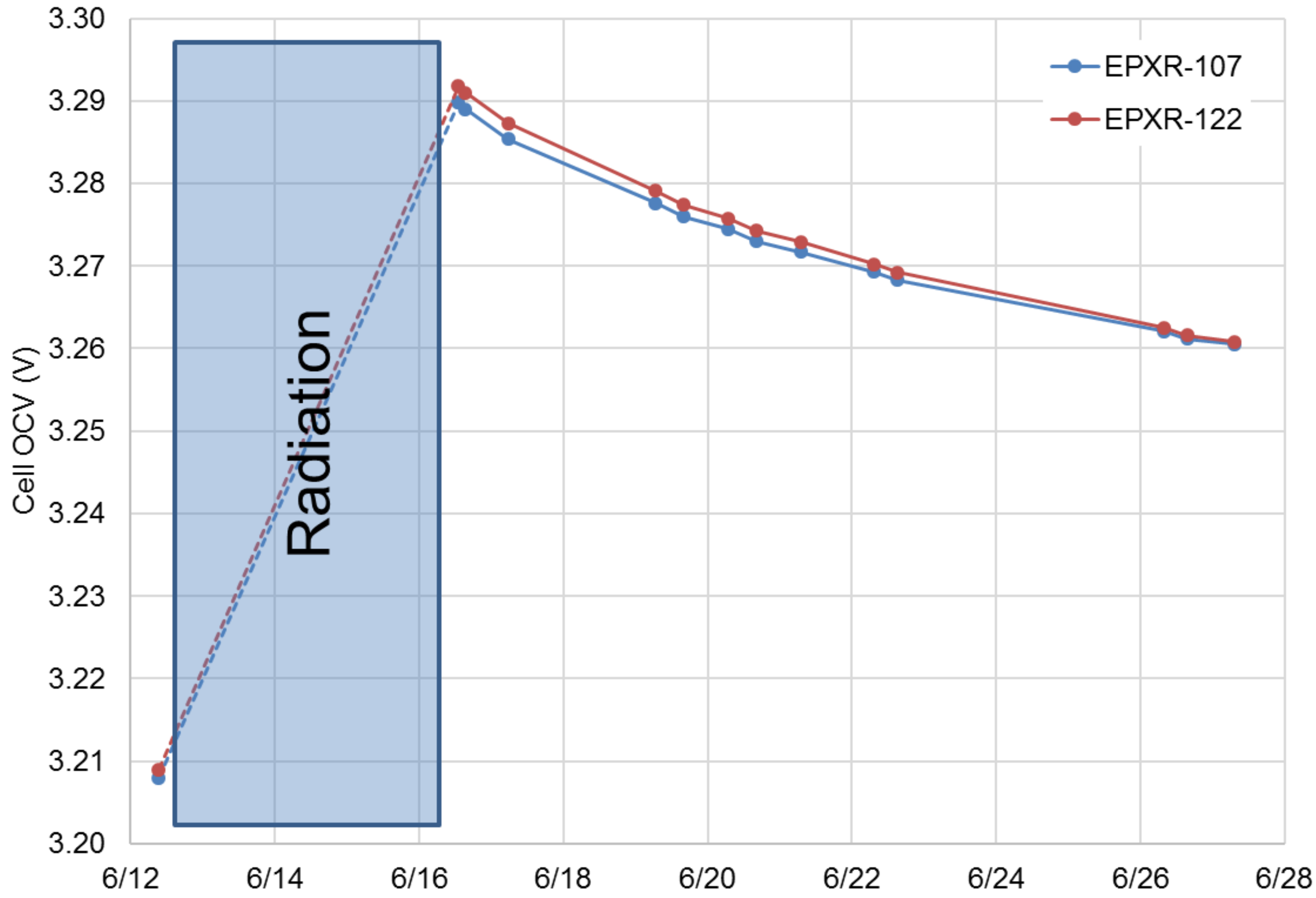
Change in operating temperature opens up possibility of pure Li/CF_x

Li/CF$_x$ discharge at 0ºC and 50 mA



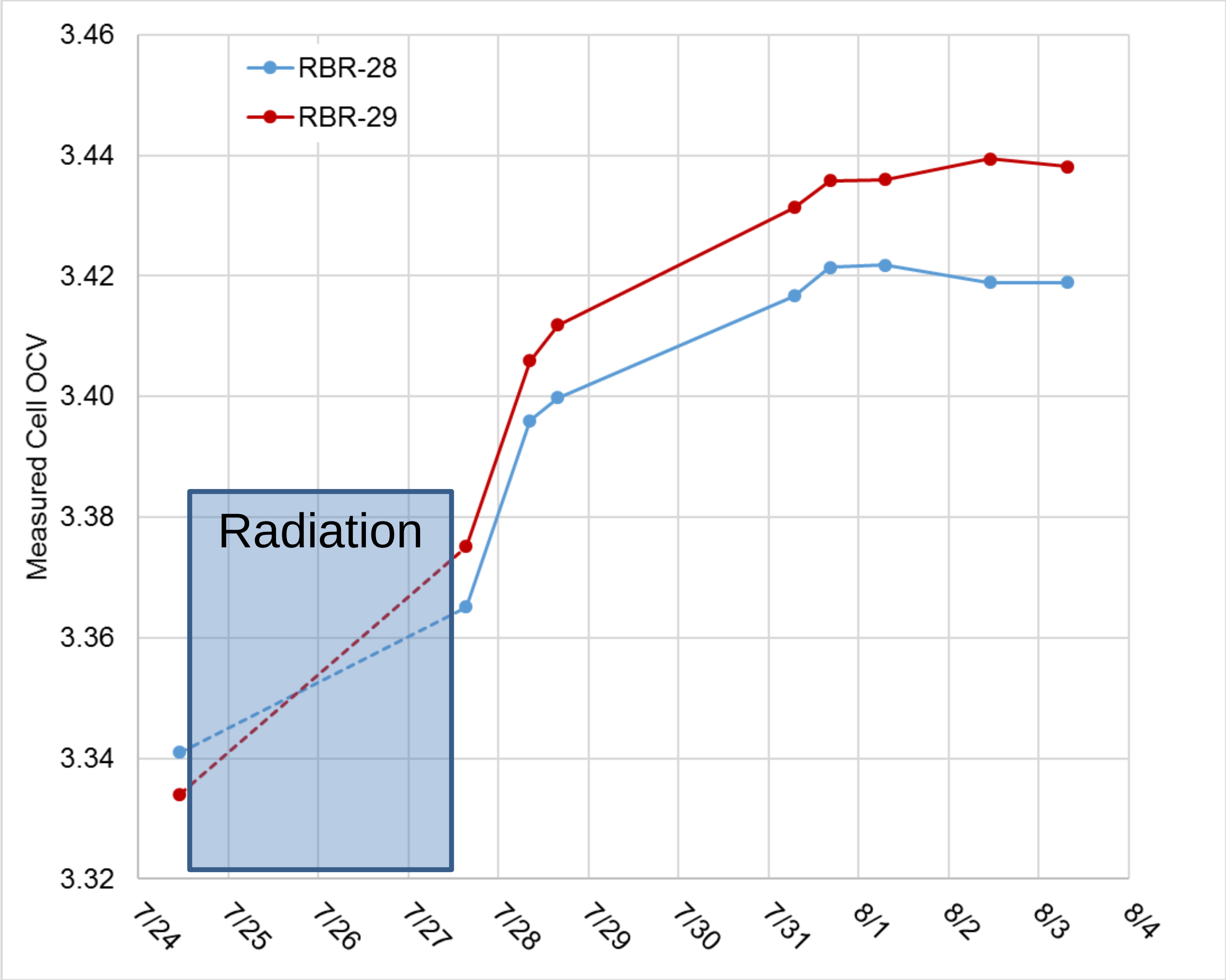
Very similar performance at moderate temperature for two different cell designs

Evolution of OCV following 10 MRad irradiation of Li/CF_x-MnO_2



OCV increases during irradiation, then slowly tapers off

Evolution of OCV following 10 MRad irradiation of Li/CF_x



OCV increases during irradiation, then rapidly immediately after, followed by a slower second increase, prior to taper

Summary

- **Different primary battery chemistries can be adapted to different performance requirements**
  - Li/FeS_2 provides excellent performance at low temperature
  - Li/CF_x-MnO_2 is better at moderate to high temperatures

- **Significant heat generation from CF_x must be considered in final battery design**

- **Starting to address unusual radiation response**
  - Electrochemical impedance spectroscopy of pristine, irradidated and partially discharged cells
  - Planned destructive physical analysis of cells, to analyze irradiated cell components

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